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Revisitation of Cycloheptatriene Derivatives as a Building Block for Various Substituted and Fused 1,6-Methano[10]annulenes and Substituted 4,9-Methanothia[11]annulenes

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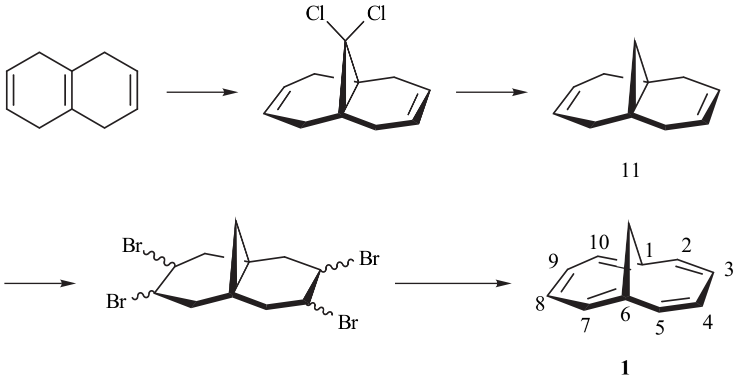
Abstract: A synthetic maneuver from 1,6-diacetyl- and 1,6-diformyl-1,3,5-cycloheptatrienes toward various 1,6-methano[10]annulenes, such as diaryl-substituted, cyclobutene-annulated, and thiophene-annulated derivatives and its quinodimethane-type compound, and 4,9-methanothia[11]annulenes is spotlighted based on our recent research efforts. The crystal structure analysis of the annulenes, discussion of mechanistic details of a key cyclization step and application of some annulene derivatives to a material in organic electroluminescent devices are also described.

Keywords: cyclobutenes, quinodimethanes, thiophenes, X-ray crystallographic analysis, molecular orbital calculations, organic electroluminescent device.

INTRODUCTION

In 1964, Prof. Emanuel Vogel, a pioneer in annulene chemistry along with Profs Franz Sondheimer, Masazumi Nakagawa, and Virgil Boekelheide, accomplished an outstanding approach in the field of structural organic chemistry by synthesizing 1,6-methano[10]annulene (**1**) as the first successful example of bridged annulenes [1]. The bridge was noted to be extremely important not only for maintaining the planarity of a large annulene ring but also for monitoring the aromatic character of the molecule by NMR spectroscopy. Annulene **1** was synthesized from tetrahydronaphthalene in 4 steps (Scheme **1**) at first [2,3]. The aromatic character of **1** is evident from various spectroscopic measurements [4] and also appears in its electrophilic substitution reactions [5] which has been studied extensively by Vogel *et al*. However, the reactivity of **1** favors the synthesis of mainly 2-, 2,7- and 2,5,7,10-substituted derivatives and only a few reaction examples of the preparation of 2,5- and 2,10-derivatives were known. Later on, Vogel *et al*. reported an alternative synthetic route to **1** and its 3- and 3,4-substituted derivatives starting from the title 1,6-diacetyl-1,3,5-cycloheptatriene (**2**) as summarized in Scheme **2** [6]. It is worthy to note that access to **2** is not difficult; **2** can be prepared from commercially available 1,3,5-cycloheptatriene by two acetylations in a hundred-gram scale. By their method 1,6-diformyl-



Scheme 1. Vogel's first method of synthesizing **1**.

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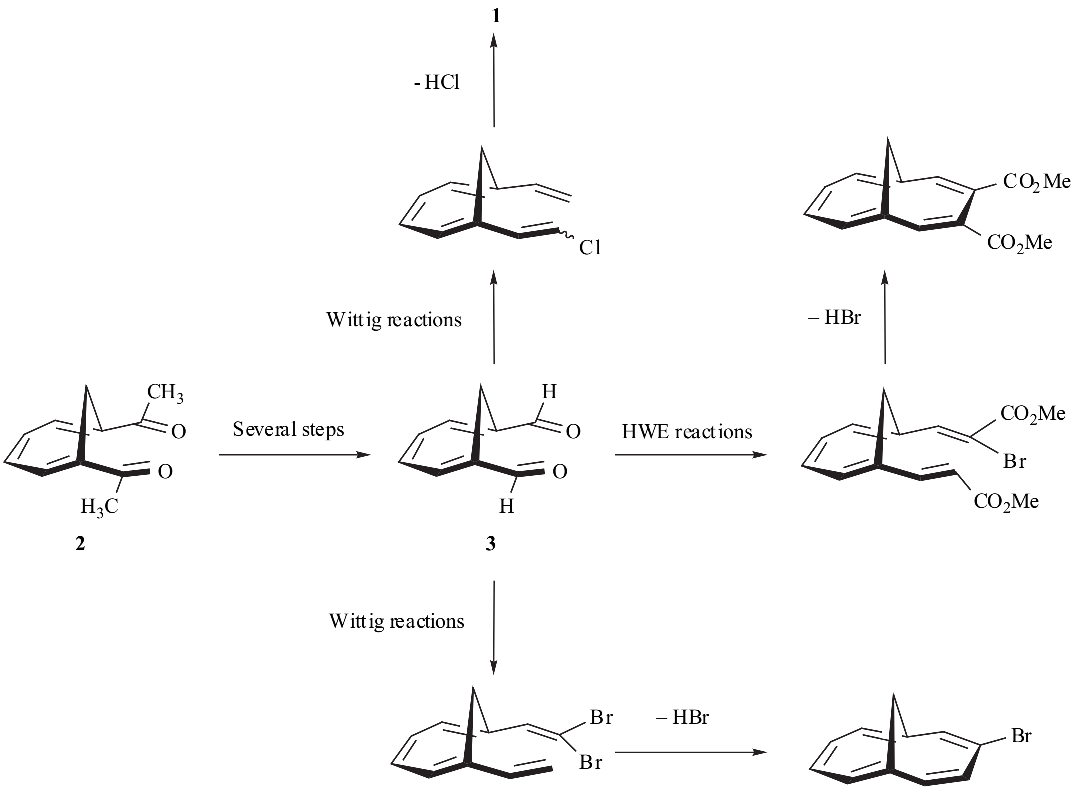
cyclohepta-1,3,5-triene (**3**) [7], prepared from **2** in 4 steps, was transformed into halogenated divinylcycloheptatrienes which finally were subjected to thermolysis to produce 1,6-methano[10]annulenes *via* electrocyclization and dehydrohalogenation. This sequence provided an important pathway to the 3- and 3,4-substituted annulenes, and thus diformyl compound **3** was also found to be a very versatile synthetic intermediate for preparing various bridged annulenes, such as muliti-bridged annulenes [6]. For the last several years we have expanded the method of Vogel *et al.* in order to synthesize novel π-conjugated organic materials having a 1,6-methano[10]annulene part by using these intermediates **2** and **3**. Herein we review (1) our synthetic efforts for preparing 2,5-disubstituted 1,6-methano[10] annulenes **4** by two different ways starting from **2**, one of which involves 4,9-methanothia[11]annulene as an intermediate, (2) application of 2,5-disubstituted 1,6-methano[10]-annulenes **4** to organic electroluminescent materials, (3) the generation and Diels-Alder reaction of the 3,4-quinodimethane compound **5**, and (4) synthesis and physical properties of the 3,4-cyclobutene-fused and thiophene-fused annulenes, **6** and **7**, from **3** (Chart **1**).

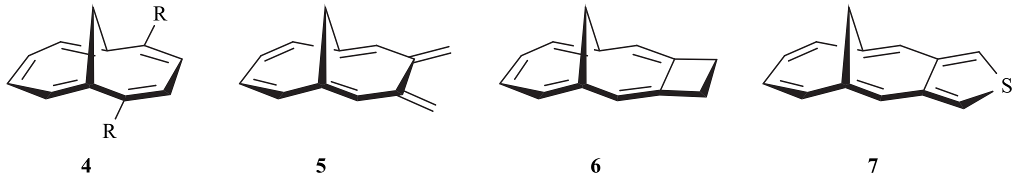
A CONVENIENT AND ATOM-ECONOMICAL SYNTHETIC METHOD FOR PREPARING 2,5-DISUBSTITUTED 1,6-METHANO[10]ANNULENES

In this section, two synthetic pathways from **2** to 2,5-disubstituted 1,6-methano[10]annulenes are described. Both are atom-economical, [8] since both methods are not required to remove one carbon atom from the acetyl groups as done in Scheme **2**. The reaction mechanism of the electrocyclization, through which one method passes, is discussed. The X-ray crystal structure analysis of one of the substituted 1,6-methano[10]annulenes is also presented.

We developed a synthetic method for preparing 2,5-disubstituted 1,6-methano[10]annulenes, outlined in Scheme **3** [9]. Reactions of **2** with an excess of Grignard reagents, methyl, phenyl, *p*-tolyl, *p*-anisyl, and 2-thienylmagnesium compounds and a hydride reagent, gave high yields (81-96% yield) of the diols **8a-e**. Treatment of **8b**, **c**, and **e** with a catalytic amount of *p*-toluenesulfonic acid (*p*-TsOH) in refluxing benzene for 0.5-1.5 h gave 2,5-disubstituted 2,3-dihydro-1,6-methano[10]annulenes **11b**, **c**, and **e** in good to high yields and **8d** with pyridinium *p*-toluenesulfonate (*p*-TsOHPy) in refluxing benzene for 20 h gave **11d** in high



Scheme 2. Vogel's alternative method for **1**.

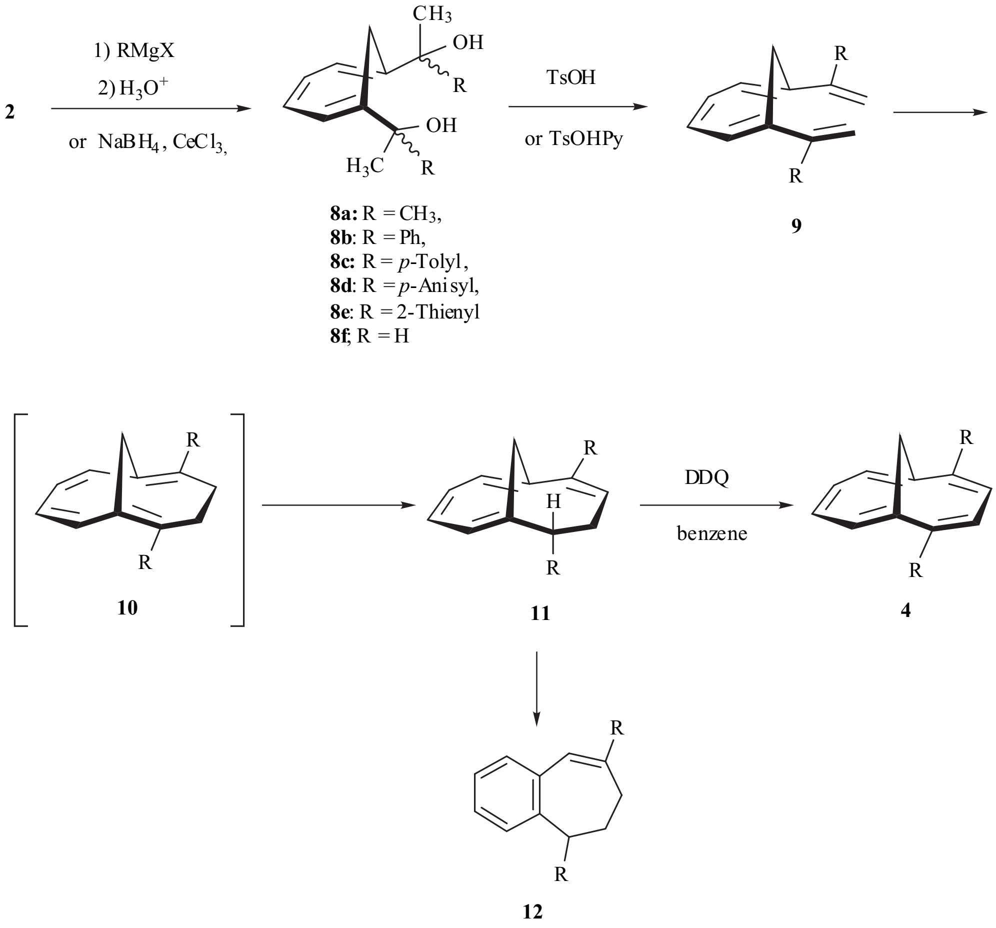


4 **5** **6** **7**

Chart 1. 1,6-methano[10]annulenes described in this review.

yield. (Table **1**) It should be pointed out that under more forcing conditions **8b-e** gave the rearranged products **12b-e** in moderate yields. On the other hand, the diol **8a** under the acidic reaction conditions afforded an unseparable mixture of **11a** and **12a**, accompanied with a substantial amount of unidentified products. It is naturally considered that these reactions are initiated by double dehydration to afford 1,6-bis(1-substituted vinyl)cyclohepta-1,3,5-trienes **9**, which undergo electrocyclization at the termini of their vinyl groups to give 2,5-disubstituted 3,4-dihydro-1,6-methano[10]annulenes **10** as seen in the experiments by Vogel *et al.* [6]. Formal 1,9-hydrogen shift from the 3 to 5 position in **10** produces **11** (*vide infra*). Indeed, intermediates **9a-d** could be isolated as a slightly unstable oil under milder acidic conditions, such as with a catalytic amount of *p*-TsOH in benzene at room temperature or *p*-TsOHPy in refluxing benzene for a short reaction period, and be independently converted to **11** under the same acidic conditions. Formation of the rearranged product **12** is thought to be derived from **11** based on the reaction conditions, and this was confirmed by independent conversion of **11** to **12**. Thus, the importance of the amount and kind of acid and the reaction temperature and period in the acid–catalyzed reaction of **8** to attain a good yield of **11** should be pointed out. It is worthy to note that dehydration of **8e** under mild acidic conditions afforded an unseparable mixture of **9e** and **10e** whose structures were fully confirmed by spectral data of the mixture. Although the reason why only **8e** afforded the mixture in contrast to other cases is not clear yet, observation of **10e** in this reaction strongly suggests that **11a-d** are also derived from **10a-d** which were not detected in similar dehydration reactions. Oxidation of **11b-e** with 2,3-dichloro-5,6-dicycano-*p*-benzoquinone (DDQ) in refluxing benzene for 1 h gave **4b-e** in 60 to 97% yields and the mixture containing **11a** was also oxidized to give **4a** in 37% yield (Table **2**). It was also found that conversion from **8** to **4** can be done by a one-flask procedure. For example, **8c** was dehydrated with 5% molar equivalents of *p*-TsOH in refluxing benzene for 30 min. Then, 5% molar equivalents of pyridine and a molar equivalent of DDQ were added to this reaction solution and this resulted mixture was refluxed for additional 1 h. The solvent was evaporated and the residue was chromatographed to give **4c** in 92% yield based on **8c** (Table **3**).

We discussed the mechanistic courses of the formation of **6**, **7**, and **9** based on semiempirical molecular orbital calculations by the PM3 method [10] with the phenyl-substituted compounds as a model. It is surprising that electrocyclization at the termini of the vinyl groups of **9** provides an efficient synthetic method for preparing the 1,6-methano[10]annulene carbon skeleton, demonstrated by our and Vogel's works [6], because the feasibility of facing of the two slightly distant π-orbitals of the vinyl groups at the 1 and 6 positions seems to be quite rare, and cycloheptatriens are known to undergo relatively facile 1,5-hydrogen shift and methylene walk rearrangement. For the



Scheme 3. The atom-economic method for preparing the annulenes **4**.

Table 1. Reaction of the Diols 8 with Acids

Entry	Diol	Acid / Condition[a]	Product	Yileld/%
1	**8a**	*p*-TsOH (10%) / r.t. / 5 h	**9a**	88
2	**8a**	*p*-TsOH (10%) / reflux / 1 h	**11a** + **12a**[b]	–
3	**8b**	*p*-TsOH (10%) / r.t. / 3 h	**9b**	76[c]
4	**8b**	*p*-TsOH (10%) / reflux / 1 h	**11b**	74[d]
5	**8b**	*p*-TsOH (10%) / reflux / 5 h	**12b**	76
6	**8c**	*p*-TsOH (10%) / r.t. / 0.5 h	**9c**	98
7	**8c**	*p*-TsOH (10%) / reflux / 0.5 h	**11c**	94
8	**8c**	*p*-TsOH (10%) / reflux / 20 h	**12c**	76
9	**8d**	*p*-TsOH•Py (5%) / reflux / 1 h	**9d**	98
10	**8d**	*p*-TsOH•Py(5%) / reflux / 20 h	**11d**	96
11	**8d**	*p*-TsOH (5%) / reflux / 2 h	**12d**	89
12	**8e**	*p*-TsOH (5%) / r.t. / 1 h	**9e** + **10e**[e]	83
13	**8e**	*p*-TsOH (5%) / reflux / 1 h	**11e**	95
14	**8e**	*p*-TsOH (5%) / reflux / 3 h	**12e**	33

a) Benzene was used as solvent for all reactions. b) The ratio of **11a** to **12a** was determined to be 3:1 by ^{1}H NMR analysis which also revealed this mixture contained a substantial amount of unidentified products. c) A 12% yield of **11b** was obtained as a minor component. d) The 10% yield of **9b** was obtained as a minor component. e) The ratio of **9e** to **10e** was found to be 1:2 by ^{1}H NMR analysis.

Table 2. Results of DDQ Oxidation of 11 in Refluxing Benzene Producing 4

Entry	Substrate	Yileld of 4[a] (%)
1	**11a**[b]	37
2	**11b**	83
3	**11c**	92
4	**11d**	97
5	**11e**	60

a) Yields after silica-gel chromatographic purification.
b) A mixture containing **11a** and **12a** was used.

thermal cyclization step of **9b** to **11b** we evaluated two possible pathways by direct disrotatory 10π electrocyclization *vs*. stepwise 6π electrocyclization, a cycloheptatriene (CHT) to a norcaradiene (NCD) form, and subsequent Cope rearrangement (divinylcyclopropane rearrangenment), outlined in Scheme **4**. Calculation results of the ground states of **9b**, **10b**, and **13b** and the transition states along the pathways clearly show that the latter stepwise route is favored over the former direct process (Fig. (**1**)). Heats of reaction ($\Delta\Delta Hf$ = 14.8 kcal mol^{-1}) for the process from **9b** to **13b** seem to be exaggerated compared with previous results by *ab initio* calculations of non-substituted CHT and NCD, and as a result activation enthalpies from **9b** to **TSa**

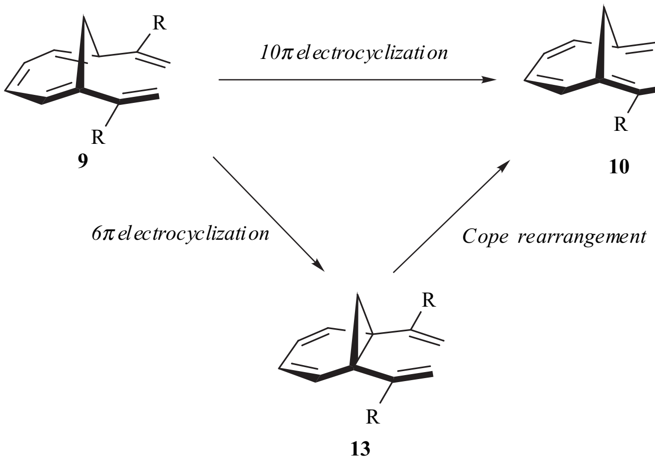
Table 3. Results of the One-Pot Procedure from 8 to 4

Entry	Diol	Conditions [a,b]	Yileld of 4[c] (%)
1	**8a**[b]	1) *p*-TsOH (10%), r.t. 5 h 2) Pyridine (10%), DDQ, reflux 1 h	19
2	**8b**	1) *p*-TsOH (10%), r.t. 1 h 2) Pyridine (10%), DDQ, reflux 1 h	84
3	**8c**	1) *p*-TsOH (5%), r.t. 0.5 h 2) Pyridine (5%), DDQ, reflux 1.5 h	92
4	**8d**	1) *p*-TsOH (5%), r.t. 1 h 2) DDQ, reflux, 1.5 h	96
5	**8e**	1) *p*-TsOH (5%), r.t. 0.5 h 2) DDQ, reflux, 1h	58

a) Benzene was used as solvent for all reactions.

b) One molar amount of DDQ to **8** was used.

c) Yields were after chromatographic purification.



Scheme 4. Two possible reaction pathways from **9** to **10**.

should be similarly exaggerated [11,12]. However, the relative difference in activation enthalpies, obtained by the calculations at this level, is valuable enough to evaluate the reaction course. Other possible reactions, such as 1,5-hydrogen shift and methylene walk rearrangement (1,5-sigmatropic rearrangement), none of which was observed in the reaction of **9b**, were calculated to be less favorable than the electrocyclization based on their calculated activation enthalpies.

Spectroscopic properties of the annulenes **4**, including chemical shifts of the bridge methyl protons, were reported in detail in our paper. Here we disclose the unpublished

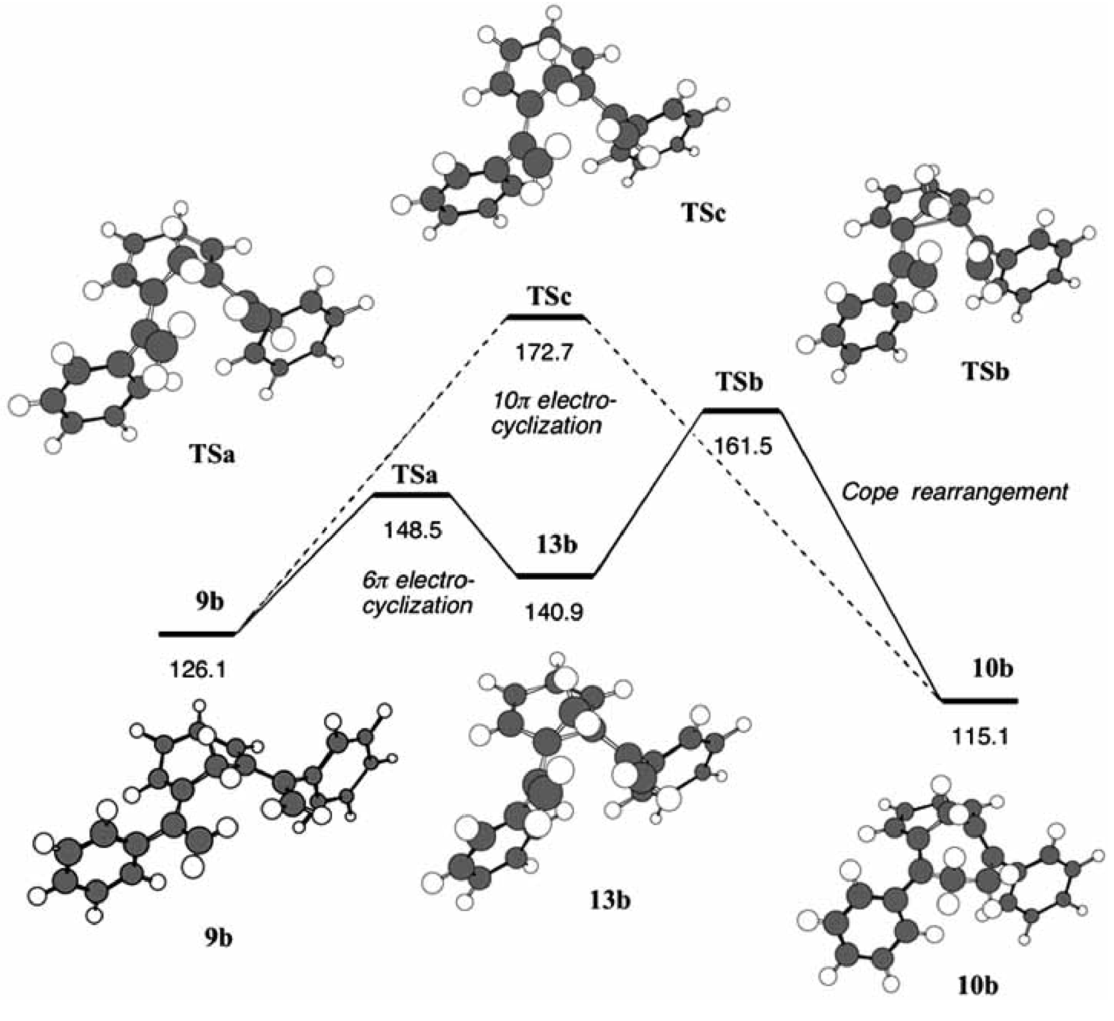


Fig. (1). Calculated energy (ΔHf in kcal mol^{-1}) diagram for conversion of **9** into **10** and optimized structures.

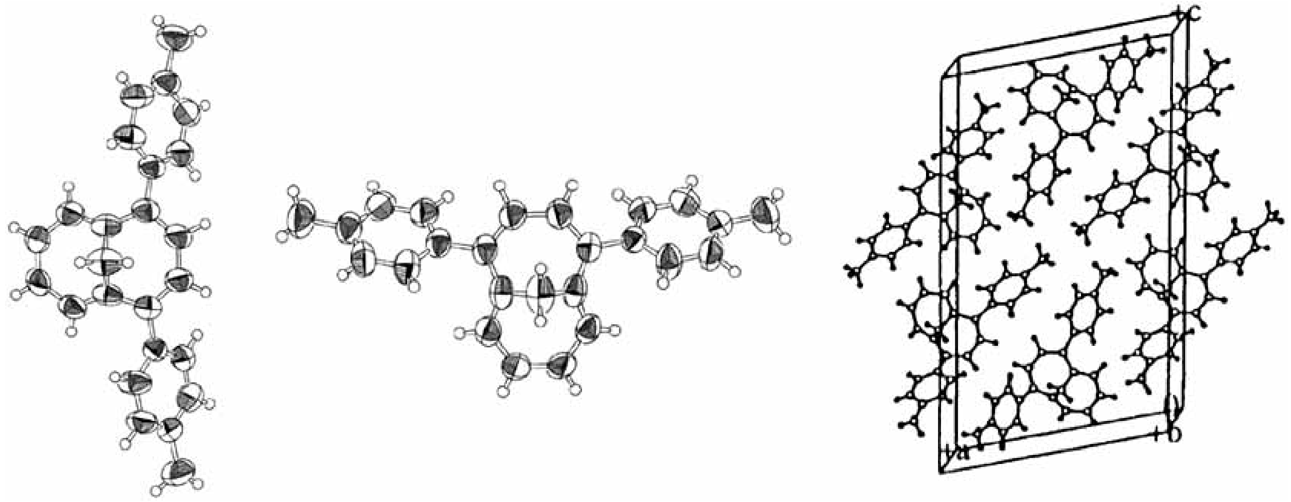


Fig. (2). ORTEP drawings and a crystal packing of **4c**.

results of the X-ray crystal structure of 2,5-di-*p*-tolylmethano[11]annulene **4c** [13]. Fig. (**2**) shows ORTEP drawings and the crystal packing of **4c**. The bond lengths and angles are demonstrated in Fig. (**3**) with those of the parent annulene **1**. The two benzene rings of the tolyl groups slant similarly from the C2-C3-C4-C5 plane with the average torsion angle of 33.7˚. Bond lengths of the C1-C2-C3-C4-C5-C6 part evidence clear bond alternation compared with those of the C1-C10-C9-C8-C7-C6 part, indicating that this compound is preferred to be contributed by the Kekulé structure **4c**(**A**) rather than by **4c**(**B**) in Scheme **5**. Since the torsion angles between the annulene and two tolyl rings are not large enough to disconnect the π-conjugation through the three rings, the π-electron system apparently denotes the UV absorptions and, therefore, the fluorescence (*vide infra*).

We have also developed another synthetic route to **4** *via* 4,9-methanothia[11]annulenes **16** [14]. Scheme **6** shows the way from **2** to **4** which involves the Grignard reaction, dehydration and desulfurization steps. Table **4** indicates the Grignard reagents, dehydration conditions, and yields from **14** to **4**. The yields were found to be largely dependent on the R groups and, however, are less than those by the method in Scheme **3**. It is worth noting that 4,9-methanothia[11]annulene **16** was isolated in two cases; 3,10-

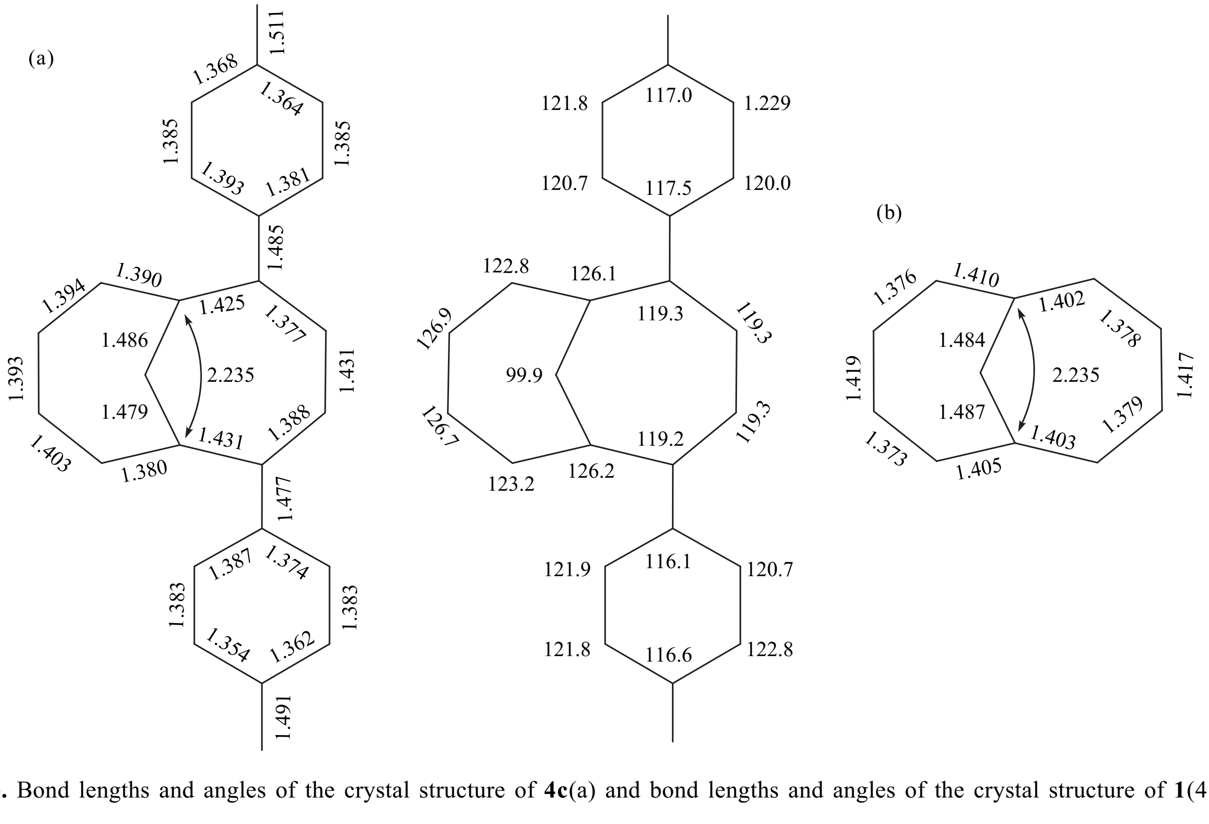
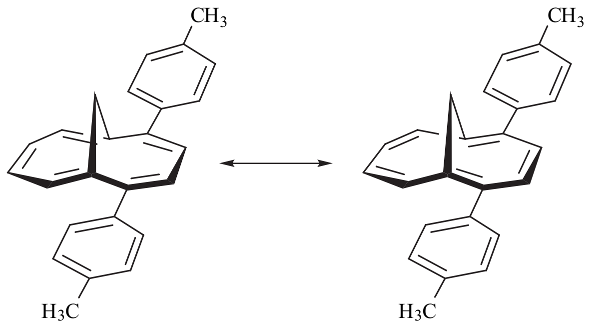


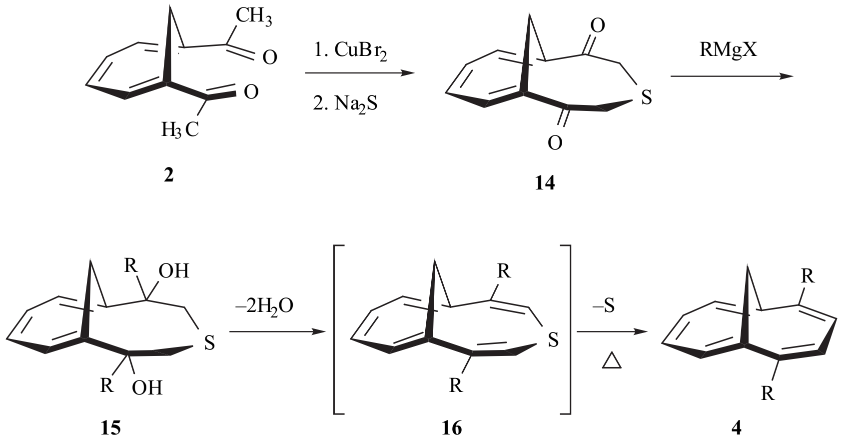
Fig. (3). Bond lengths and angles of the crystal structure of **4c**(a) and bond lengths and angles of the crystal structure of **1**(4; R=H) (b).



4c(A) **4c(B)**

Scheme 5. Resonance forms of **4c**.

di-*tert*-butyl- and 3,10-dichloro-4,9-methanothia[11] annulenes **16a** and **16b** were obtained as seen in entry 5 in Table **4** and Scheme **7**. The dichloro derivative of **16b** was obtained directly from **14** with phosphorous pentachloride in 12% yield (Scheme **7**). The reaction conditions for a longer reaction period and at higher temperature resulted in desulfurization of **16b**. The dichloro derivative of **16b** was also produced in the reaction of **14** under the Vilsmeier-Haack reaction conditions, accompanied with **17** and **18** (Scheme **8**) [15]. Synthesis of the dicyano derivative **4** (R=CN) from **14** was also examined [16]. Reaction of **14** with trimethylsily cyanide in the presence of ZnI_2 provided trimethylsilyether of the cyanohydrin **19** and the subsequent treatment with $POCl_3$ in pyridine yielded the chloro compound **20** as the sole product, which is unusual under the reaction conditions (Scheme **9**). Dehydrochlorination of **20** with DBU gave the desired dicyano derivative **4** (R=CN), probably through the intermediates **21** and **22** shown in Scheme **10**.



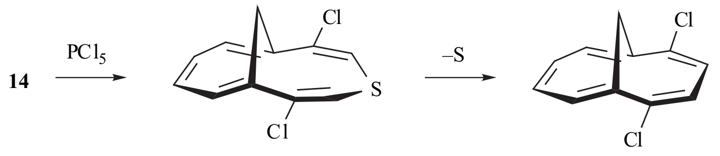
2 **14**

15 **16** **4**

16a (R= *tert*-Bu)

R = Ph, Me, Et, *i*-Pr, *tert*-Bu

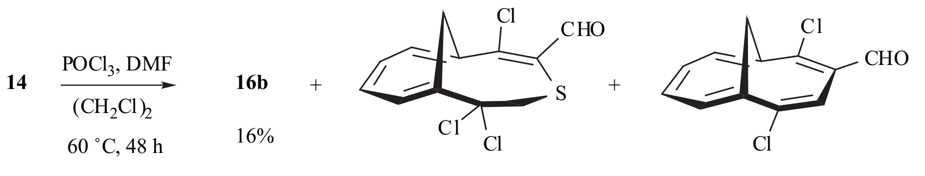
Scheme 6. Another synthetic method for **4** *via* **16** from **2**.



16b 12%

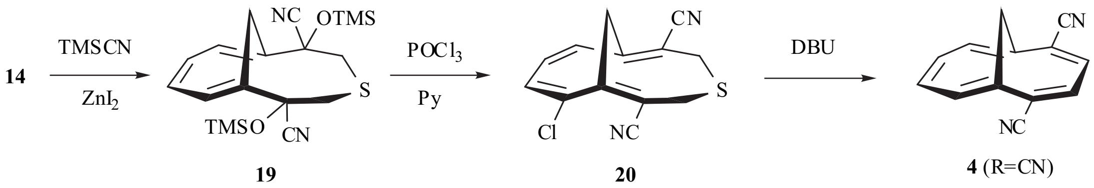
4 (R=Cl)

Scheme 7.

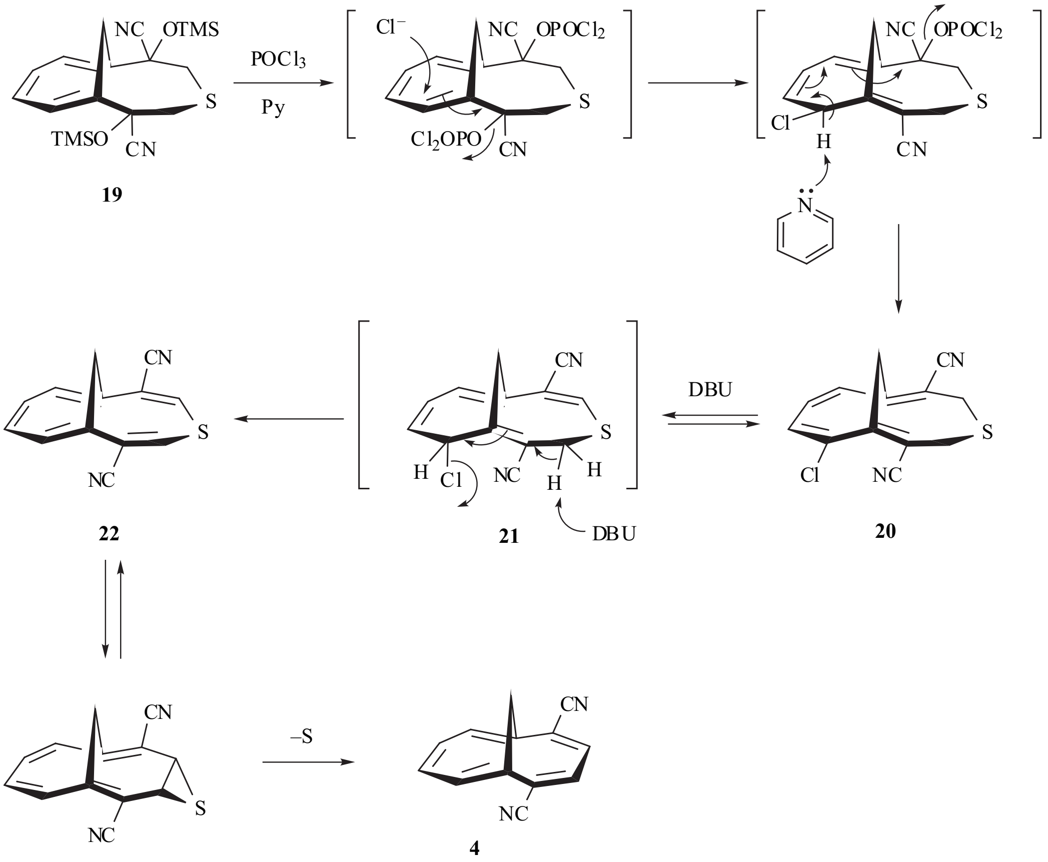


17 16% **18** 27%

Scheme 8.



Scheme 9.



Scheme 10. The plausible reaction mechanism of the formation **4**(R=CN).

Table 4. Conversion of the Thioketone 14 into 4

Entry	R groups	Conditions	Yileld of 4 [a] (%)
1	Ph [b]	1) PhMgBr, ether, r.t. 2 h	(79) [c]
		2) *p*-TsOH (10%), Ph-H, reflux 1 h	61(77) [d]
2	Me [b]	1) MeMgI, ether-THF, r.t. 2 h	(72) [c]
		2) *p*-TsOH (10%), Ph-H, reflux 1 h	24(34) [d]
3	Et [b]	1) EtMgBr, ether, r.t. 2 h	
		2) $SOCl_2$, Pyridine, 60°C, 1.5 h	30
4	*i*-Pr [b]	1) *i*-PrMgI, ether-THF, r.t. 2 h	(93) [c]
		2) $SOCl_2$, Pyridine, 60°C, 1.5 h	15(16) [d]
5	*tert*-Bu	1) *tert*-BuMgCl, ether-THF, r.t. 2 h then, $SOCl_2$, Pyridine, 60°C, 0.5 h	(10) [e]
		2) 110°C, 6 h	10(100) [f]

a) Isolated yield of **4** by two-step procedures after chromatography purifications. b) Unpublished results. c)Yields in parentheses are ones forming **15**. d) Yields in parentheses are ones of the second dehydration-desulfurization step. e) Yield in parentheses is one forming **16** by two-step procedure. f) Yield in parentheses is one of the desulfurization step.

STRUCTURAL AND CONFORMATIONAL ANALYSES OF 4,9-METHANOTHIA[11]ANNULENES

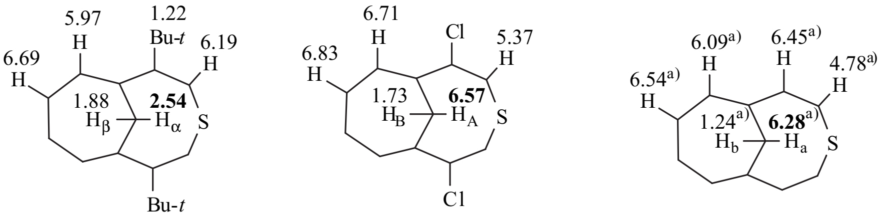
In the previous section, two new ways to synthesize 2,5-substituted 1,6-methano[10]annulenes were introduced. One of the ways provides the 1,6-methano[10]annulenes *via* desulfurization of intermediary 4,9-methanothia[11]annulenes under the reaction conditions and two 4,9-methanothia [11]annulenes were isolated. In this section, the structural and conformational analyses of these two 4,9-methanothia [11]annulenes **16a** and **16b** (R= *tert*-Bu and Cl) are described [14].

In 1972, Vogel *et al.* reported the successful synthesis of the parent compound of 4,9-methanothia[11]annulene **16c** (R=H) which was claimed to have the *syn* conformation in respect of the stereochemical relationship between the methano bridge and the sulfur atom based on the spectroscopic data [17]. Selected spectroscopic data of three methanothia[11]annulenes, **16a**, **16b** and **16c**, are listed in Fig. (**4**). The critical differences between them were shown in the chemical shift value of one of the methylene hydrogens and the absorption wavelength in the UV absorption spectrum. The H_α of **16a** in the ^{1}H NMR spectrum appears at the normal aliphatic region (δ = 2.54 ppm), while the H_a and H_A of **16c** and **16b** resonate at abnormally low field (δ = 6.28 and 6.57 ppm, respectively). The latter phenomenon was reasonably explained by the combined effects of the diamagnetic anisotropy of the sulfur-carbon bonds and the field effect and a steric compression of the sulfur atom, as reported by Vogel. Thus, the chemical shift value of H_α indicates that this hydrogen atom is distant from the sulfur atom in the molecular structure of **16a**, presenting that **16a** has a different conformation from **16b** and **16c**. Although the ^{1}H NMR spectra of **16a** and **16b** were recorded at a range of temperatures between –100 and +100 °C with either a mixture of dichloromethane-d_2 and carbondisulfide, chloroform-*d*, or dimethylsulfoxide-d_6 as solvent, no dynamic behavior, such as ring-flipping and cycloheptatriene-norcaradiene equilibrium, was observed. The UV spectrum of **16a** with only shoulder absorptions at 248 and 279 nm differs from those of **16b**, **16c**, and the corresponding hydrocarbon, bicyclo[5.4.1]dodeca-2,5,7,9,11-pentaene (λmax = 248 and 327 nm), and its long wavelength maximum is rather close to that (λmax = 245 nm) of 1,6-*bis*(hydroxymethyl)-1,3,5-cycloheptatriene. Thus, the triene part of the seven-membered ring is indicated to be disconnected from the divinyl sulfide part and the former moiety mainly contributes the long wavelength absorption. From these spectroscopic data, it is concluded that in solution **16a** exists entirely as an *anti* conformer in which a large torsion angle through the C2-C3-C4-C5 (or C8-C9-C10-C11) carbons is expected, while **16b** exists as a *syn* conformer with its effective π-conjugation through the pentaene part.

The molecular structures of **16a** and **16b** were further elucidated by X-ray crystallographic analysis. ORTEP drawings and the crystal packing are shown in Fig. (**5**) and (**6**), respectively. There are two independent molecules with *C1* symmetry in the crystal of **16a** with very little differences in the bond lengths. As clearly shown in Fig. (**6**), **16a** has the *anti* conformation with the average non-bonded atomic distance of 3.51 Å between the sulfur and the C12 carbon atoms. The thiaanulene rings of these two molecules face each other in the opposite direction with the sulfur atoms inside and the methano bridges outside in the crystal (Fig. (**6**)). As expected above, average torsion angles for the C2-C3-C4-C5 and C7-C8-C9-C10 carbons of the two molecules are 79.4 and 77.1°, respectively, which are large enough to disconnect the π-conjugation between the cycloheptatriene and the divinyl sulfide parts.

The X-ray structure of **16b** shows *Cs* symmetry and has the *syn* conformation with the non-bonded atomic distance of 3.12 Å between the sulfur and the C12 carbon atoms. The torsion angle for the C2-C3-C4-C5 carbons of **16b** is 17.9° in contrast to the case of **16b**. From these structural data, it is clearly revealed that the di(*t*-butyl) derivative **16a** exists as an *anti* conformer and the dichloro derivative **16b** exists as a *syn* conformer both in solution and in solid state.

The density functional calculations at the BLYP/6-31G* level of theory on **16a** and **16b** support these spectroscopic and X-ray crystallographic findings. Although the optimized structure of a *syn* conformer and none of an *anti* conformer for **16c** was obtained, those of the *syn* and *anti* conformers for **16a** and **16b** were obtained (Fig. (**7**)). Thus, **16c** is suggested to have a single-well potential in contrast to the inspection by Drieding models, while **16a** and **16b** have a double-well potential. The *anti* conformer of **16c** is predicted to be more stable than the *syn* conformer by 5.0 kcal mol^{-1}, and the *anti* conformer of **16b** less stable than the *syn* conformer by 4.9 kcal mol^{-1}, supporting experimental facts. Steric repulsion between the hydrogen atoms at the 5 and 8



16a

λ_{max} (hexane) = 248sh (3.79), 279sh (3.50) nm.

16b

λ_{max} (hexane) = 242 (4.40), 287 (4.34), 397 (2.52) nm.

16c

λ_{max} (cyclohexane) = 233 (4.49), 284 (4.43), 395 (2.63) nm.$^{a)}$

Fig. (4). ^{1}H NMR chemical shifts (δ ppm in chloroform-*d*) and UV absorption maxima (log ε in parentheses) of **16a**- c. a) Taken from Ref. [17].

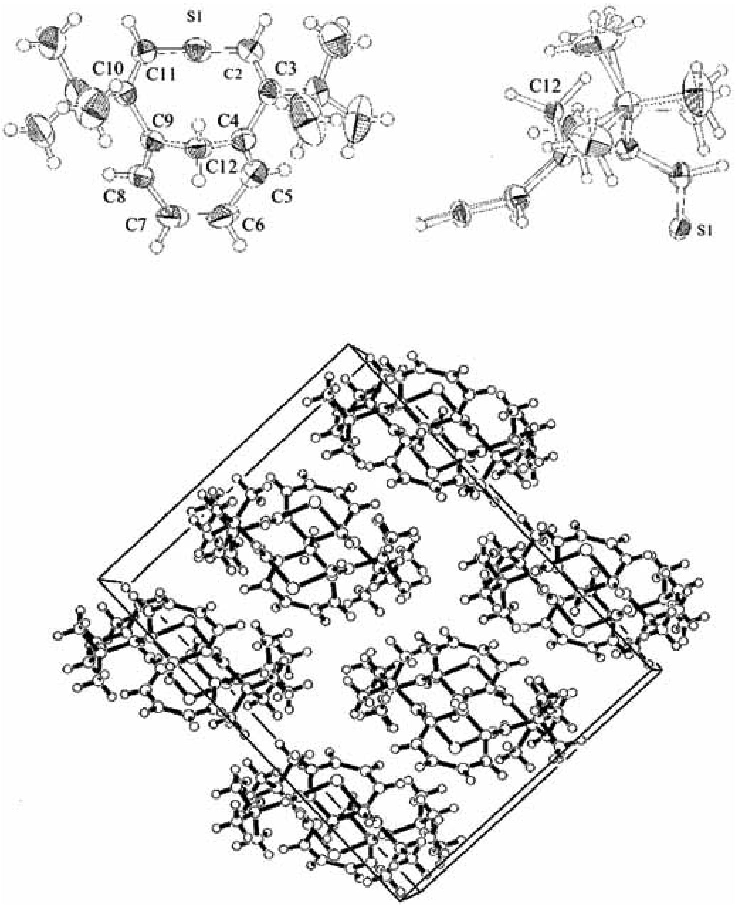


Fig. (5). The ORTEP drawings and crystal packing of the 4,9-methanothia[11]annulene **16a**.

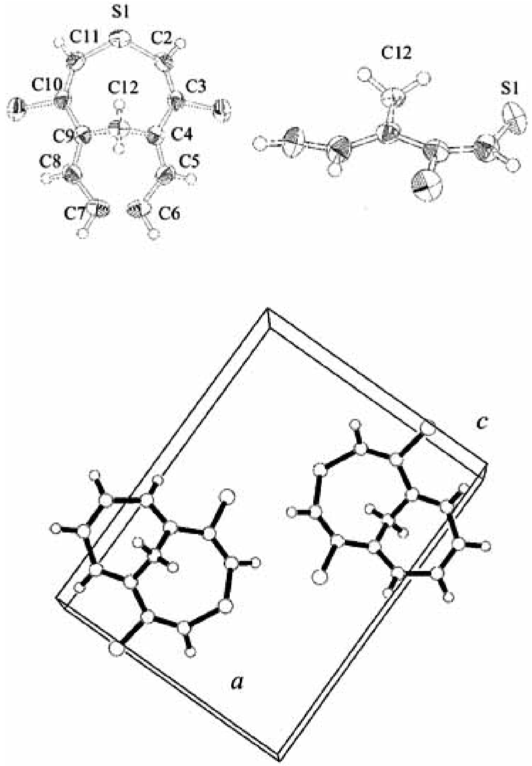
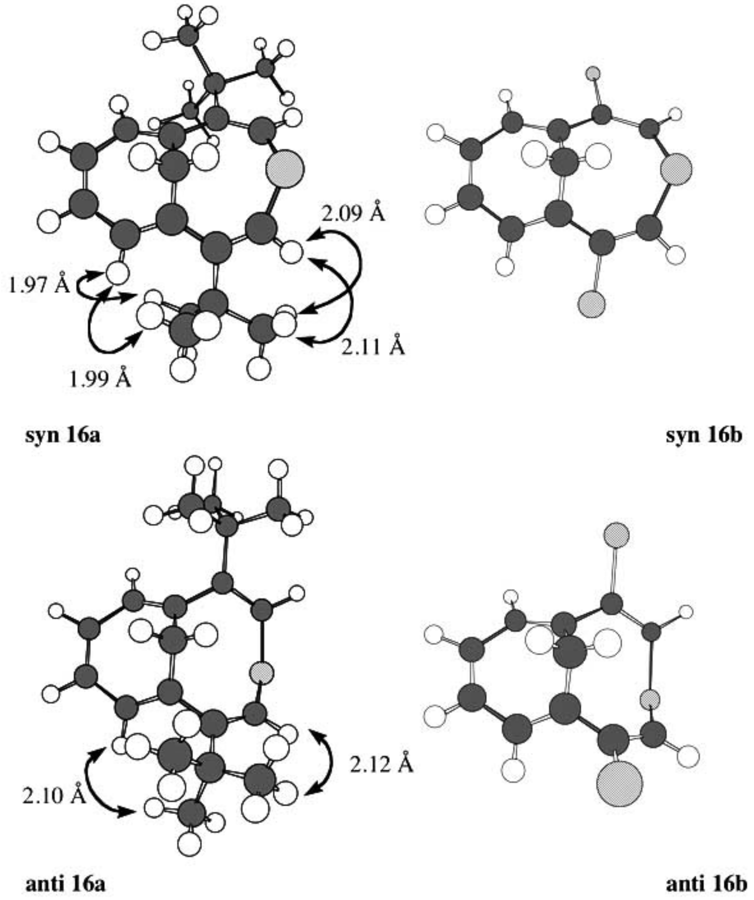


Fig. (6). The ORTEP drawings and crystal packing of the 4,9-methanothia[11]annulene **16b**.



syn 16a **syn 16b**

anti 16a **anti 16b**

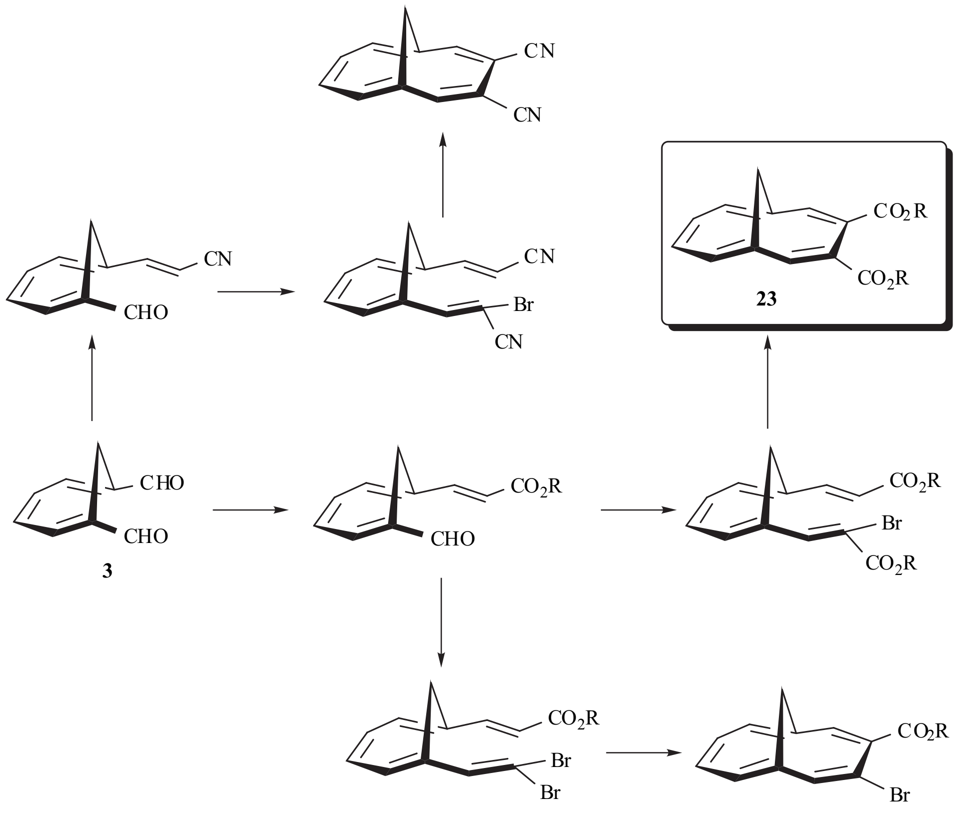
Fig. (7). Optimized structures (Chem3D output) of syn- and anti-conformers for **16a** and **16b** at the BLYP/6-31G* level of theory and selected short non-bonded atomic distances.

positions in the *syn* conformer and the *t*-butyl groups accounts for its instability; the non-bonded atomic distances between the hydrogens at the 5 and 8 positions and the closest ones of the *t*-butyl groups are 1.97 and 1.99 Å in the optimized structure of the *syn* conformer. No such short non-bonded atomic distance less than 2.0 Å is observed in the *anti* conformer.

The conformational difference between **16a** and **16b** is reflected in their chemical behavior. Although the parent **16c** was reported to undergo desulfurization at 50 ˚C, **16a** and **16b** were reluctant to that at the same temperature. Compound **16b** gradually undergoes desulfurization at above 80 ˚C and **16a** at above 120˚C to give the corresponding methano[10]annulenes **4**, respectively, in a quantitative yield. At 120 ˚C in dimethylsulfoxide-d_6, half-life times, measured by NMR analysis, of **16a** and **16b** were 3.75 h and 9.2 min, respectively. The chemical behavior and conformation had been rationalized by the results of DFT calculations.

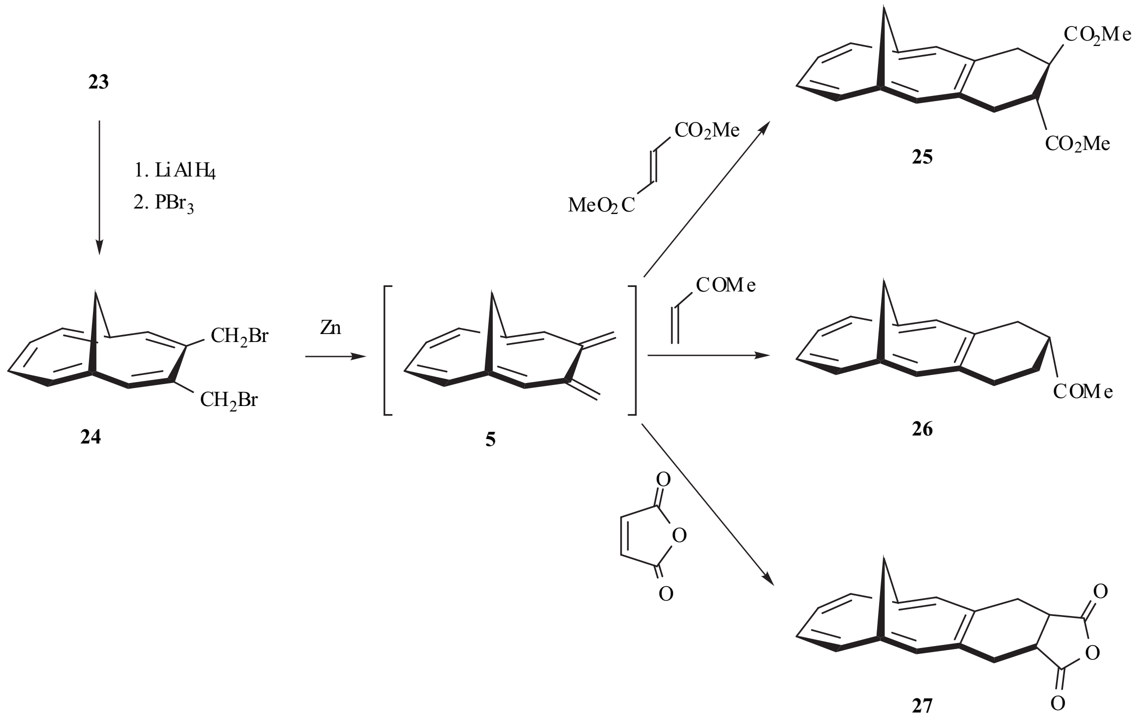
1,6-METHANO[10]ANNULENE-3,4-QUINODIMETHANE FROM 1,6-DIFORMYL-1,3,5-CYCLOHEPTATRIENE

In the first section of this review, the synthesis of 2,5-disubstituted 1,6-methano[10]annulenes from 1,6-diacetyl-1,3,5-cycloheptatriene (**2**) is described. Since these annulene derivatives can not be transformed from the parent **1**, the method provides unexchangeable and efficient protocols for these derivatives. In the next three sections including this, synthetic ways of the 3,4-substituted annulenes, such as theoretically and/or synthetically interesting compounds, **5**, **6** and **7**, are covered. Some years after Vogel's finding of an effective synthetic route from 1,6-diformyl-1,3,5-cycloheptatriene (**3**) to 3- and 3,4-disubstituted derivatives by the Wittig and its closely related reactions as shown in Scheme **2**, Neidlein and Kataky independently improved this method and showed that various derivatives can be transformed as shown in Scheme **11** [18, 19]. Particularly, diester **23** can be obtained in a very good total yield. Therefore, we employed this diester as a synthetic intermediate to generate 1,6-methano[10]annulene-3,4-quinodimethane (**5**) [20] which had remained unknown in spite of the fact that many quinodimethanes were known in benzenoid and heteroatom-containing aromatics and are well utilized for constructing bi- and polycyclic ring systems [21]. Generation of **5** was confirmed by formation of the [4+2]adducts **25-27** in the zinc reduction of the bisbromomethyl derivative **24**, prepared from **23**, in the presence of various dienophiles (Scheme **12**). Dimethyl acetylenedicarboxylate also provided the adduct **28** which was dehydrogenated using Pd-C to yield the anthracene-like

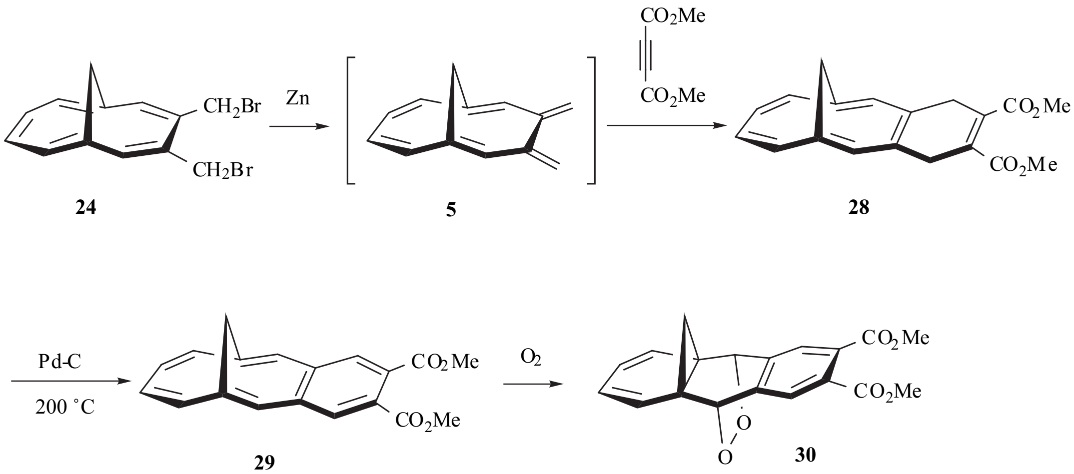


Scheme 11.

compound **29**. It is worthy to note that **29** shows high reactivity against molecular oxygen; allowing an acetone solution of **29** to stand under room light provided a quantitative yield of the endoperoxide **30**. The results suggest that **29** itself works as a sensitizer to generate singlet oxygen and adds to it, just like fullerenoids do [22].



Scheme 12. Generation and trapping of quinodimethane (**5**).



Scheme 13.

CYCLOBUTENE-FUSED 1,6-METHANO[10] ANNULENE

The structures and reactivity of small ring-annulated aromatic compounds have fascinated organic chemists for a long time [23]. Particularly, an effect of ring strain impeded by the small ring on its aromaticity and electronic structure was often studied. Although such abundant benzenoid molecules were synthesized and their structures and reactivity were scrutinized, very few of the nonbezenoid molecules were studied. So as in the chemistry of 1,6-methano[10]annulene, the cyclopropene-fused 1,6-methano[10]annulene **31** (Chart **2**), as the only such example, was synthesized by Vogel *et al*. in 1974 [24] and the cyclobutene-fused one **6**, a valence isomer of **5**, had been unknown until we succeeded in its synthesis in 2004 [25].

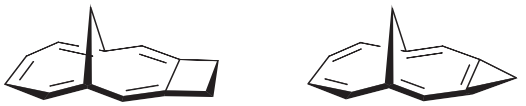
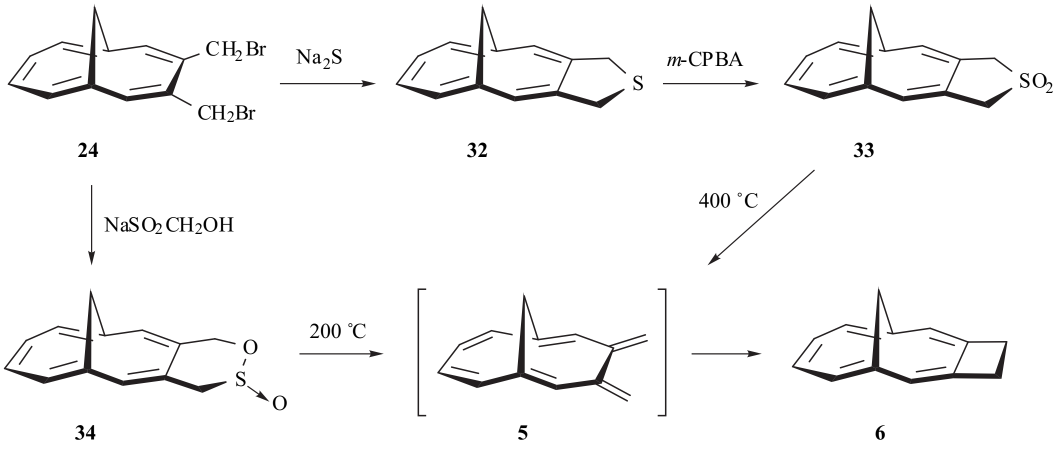


Chart 2. Small-ring annelated 1,6-methano[10]annulenes.

Synthesis of **6** from the *bis*-bromomethyl derivative **24** was achieved by the way shown in Scheme **14**. Thermolysis of sulfone **33** and sulfinate **34** provided **6**, *via* **5**, in good yields. The ^{1}H NMR spectrum of **6** reveals that the bridged methylene protons appear at higher magnetic field and the ring protons at lower field than those of the parent **1**, clearly indicating slightly greater diatropicity of **6** compared with that of **1** (Fig. (**8**)). This result is in contrast to the fact that while benzocyclobutene **35** shows diminished diatropicity compared with benzene [26], naphthocyclobutene **36** shows comparable diatropicity compared with naphthalene. The ring current of an aromatic compound is in general affected by the ring size; the larger area of an aromatic ring indicates greater diatropicity. Therefore, this phenomenon may be explained by the slight enlargement of the [10]annulene ring area, which is derived from counteraction based on the shrinking of the 3,4 positions of the ring caused by the cyclobutene-annulation. This structural change also causes a little elongation of the through space atomic distance at the bridged positions of the annulene ring and, thus, the π−π interaction at the positions should be concurrently diminished to affect a ring current effect which appears as a 10π-ring effect rather than a naphthalene-like two 6π-ring effect.

Besides structural characteristics, the chemical behavior of **6** was also studied. Electrophilic substitution reactions of **6** resulted in preference of the 9(12)-substituted products



Scheme 14.

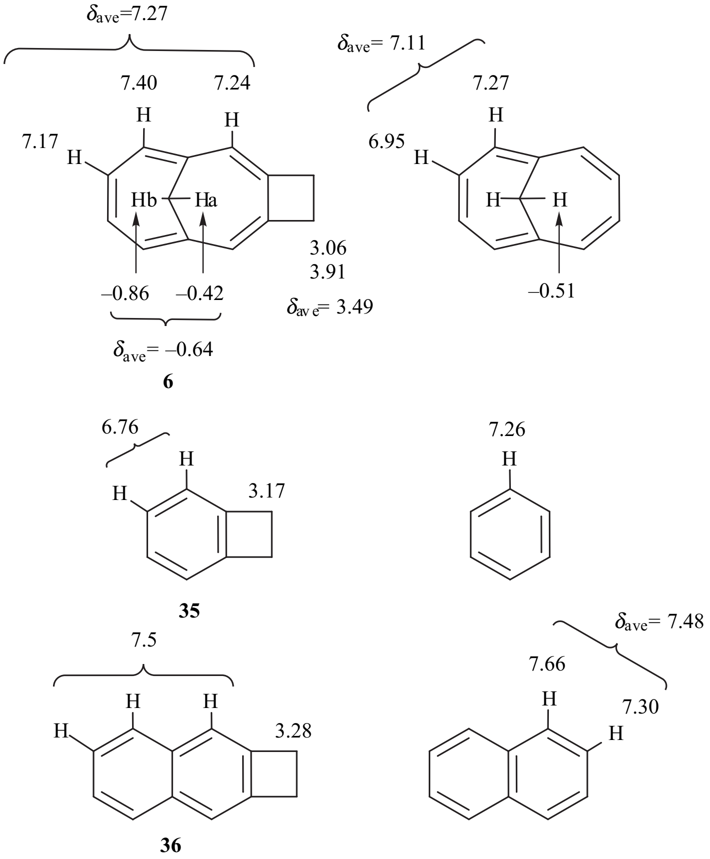


Fig. (8). ^{1}H NMR chemical shifts (δ_{ppm}) of **6**, **4** (R=H), benzocyclobutene (**35**), benzene, naphtocyclobutene (**36**), and naphthalene.

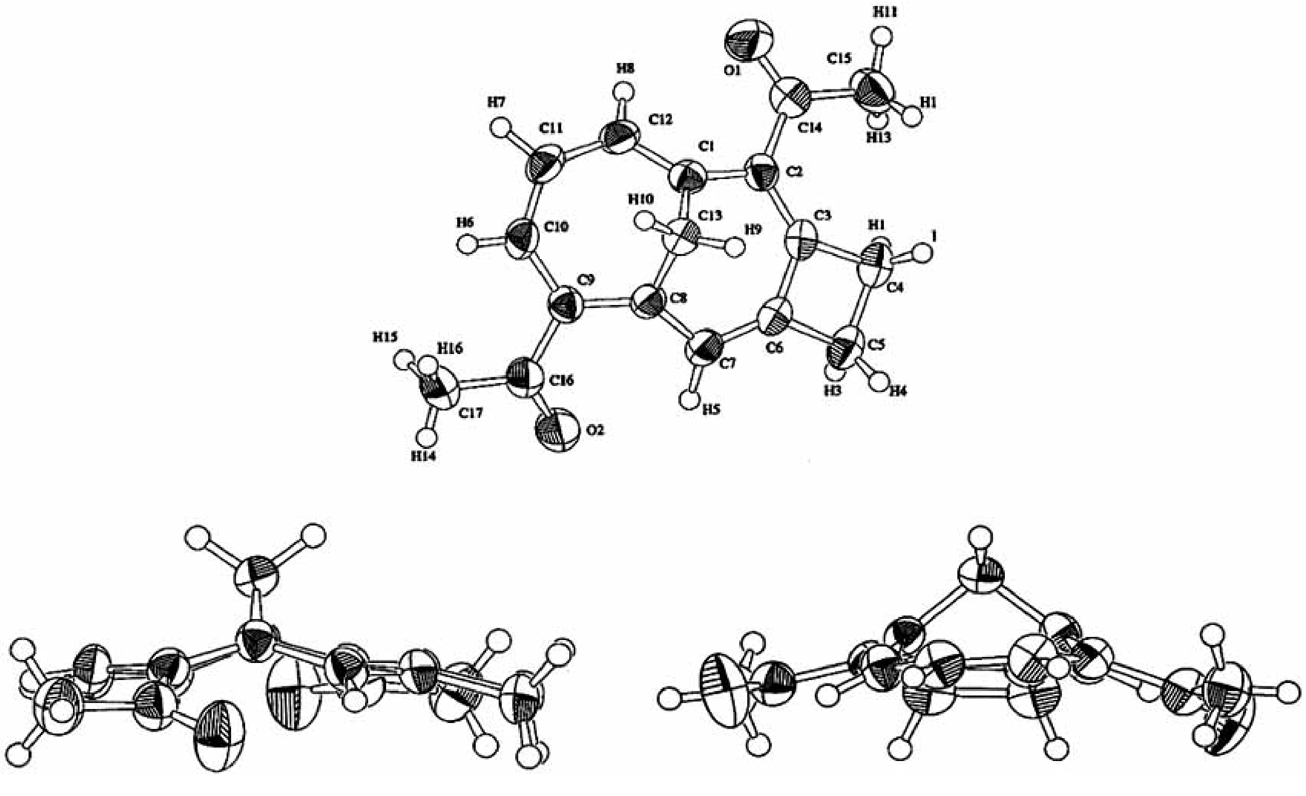
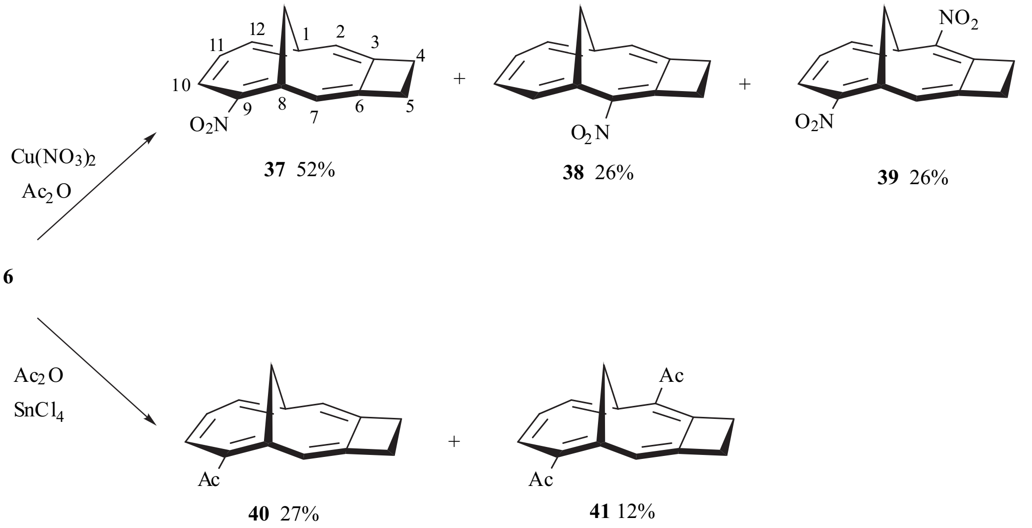


Fig. (9). ORTEP drawings of 2,9-diacetyl annulene **41**. The numbering shown is according to our system.



Scheme 15. Electrophilic substitution reactions of **6**.

(Scheme **15**). The selectivity at the 9(12) position over the other peri-position, the 2(7) position, in those reactions can be referred to as a Mills-Nixon effect [27] and can be explained based on the nature of the frontier orbitals; semiempirical molecular orbital calculations predict greater coefficients in the next HOMO at the 9(12) position relative to the 2(7) position. Also, the solid-state structure of the product **41** was elucidated by X-ray analysis (Fig. (**9**)) to reveal slightly longer distance at the bridged positions (2.322 Å) and the bond alternation favoring the resonance form **41(A)** rather than **41(B)** as shown in Scheme **16**. DFT calculations of **6** at the B3LYP/6-31G* level of theory also predict a slightly longer distance at the positions (Fig. (**10**)) relative to that of **4**. As has been noted by Simonetta [28], this difference is small but critical for the through-space interaction at the bridging position, since the interaction is possible when the distance is less than 2.3 Å. These results partially support the structural change deduced from its tropicity.

1,6-METHANO[10]ANNULENO[3,4-*C*]THIOPHENE

There have been synthesized some benzene-annulated 1,6-methano[10]annulenes, **29**, **42**, **43** by us [20], Vogel *et al.* [29] and others [30]. The diatropic nature of the annulene ring in **29** and **42** was found to be fairly reduced judging from the chemical shifts of the bridging methylene protons compared with **1** and the dibenzo derivative **43** exists as a norcaradiene form. The former phenomenon can be recognized as a fact that a more stabilized aromatic ring can survive to destroy a less stabilized aromatic ring, though condensation of aromatic rings sometimes constructs a new electronic structure with delocalized π-electrons around the whole newly-formed carbon framework as seen in isobenzothiophene which consists of benzene and thiophene. We were interested in thiophene-annulated 1,6-methano[10]annulenes as a diatropic compound, since thiophene shows less aromatic stabilization energy than benzene does. In 1992, Neidlein reported synthesis of 1,6-methano[10]annuleno[3,4-*b*]thiophene derivative **44** which indeed indicates diatropicity [31]. Later, we synthesized the isomeric 7 and its dicyano derivative **45** and also elucidated their crystal structures [32] (Chart **3**).

Synthesis of **45** was achieved from the *bis*-bromomethyl derivative **24** as shown in Scheme **17**. Non-substituted **7** was obtained as slightly unstable yellow crystals from sulfide **32** *via* dehydration of the sulfoxide using Al_2O_3. An

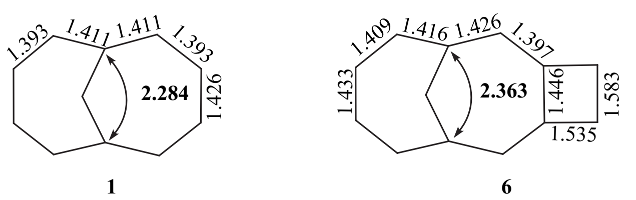
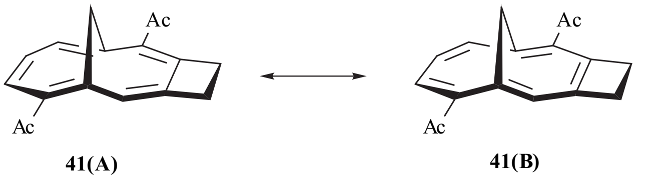


Fig. (10). Atomic distances (Å) of the structures of **1** and **6** calculated by the B3LYP/6-31G* level of theory.



Scheme 16. Resonance forms of **41**.

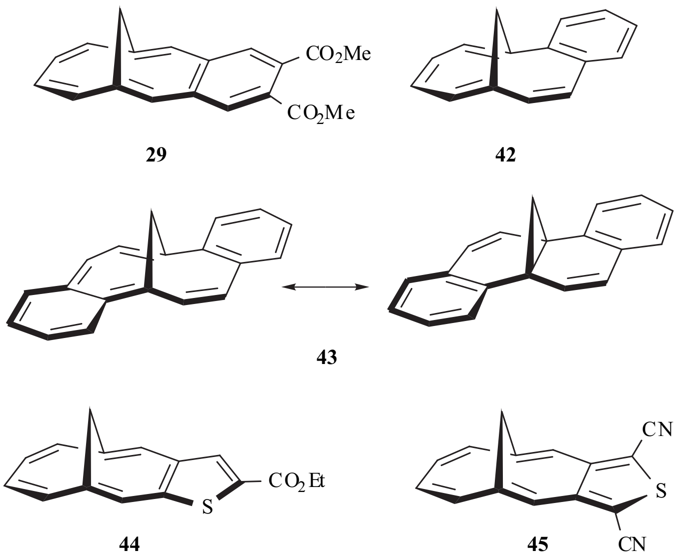
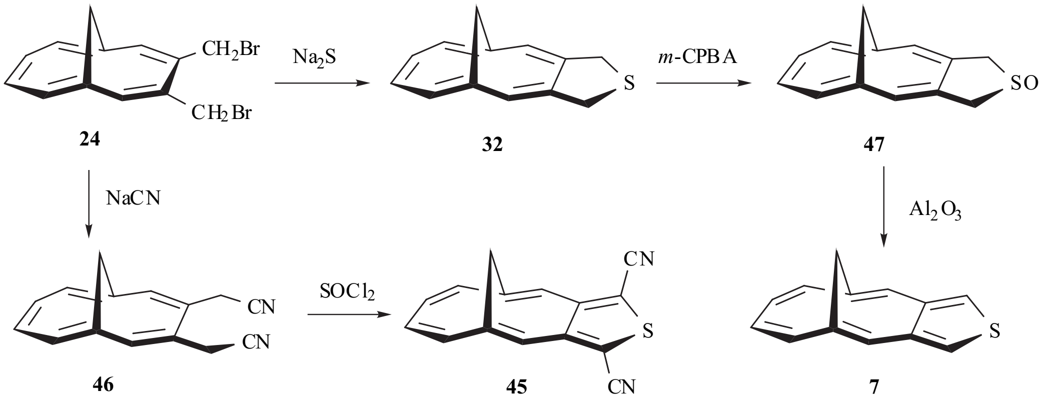


Chart 3. Benzo- and thiophene-annelated 1,6-methano[10]annulenes.



Scheme 17. Synthetic schemes to **7** and **45**.

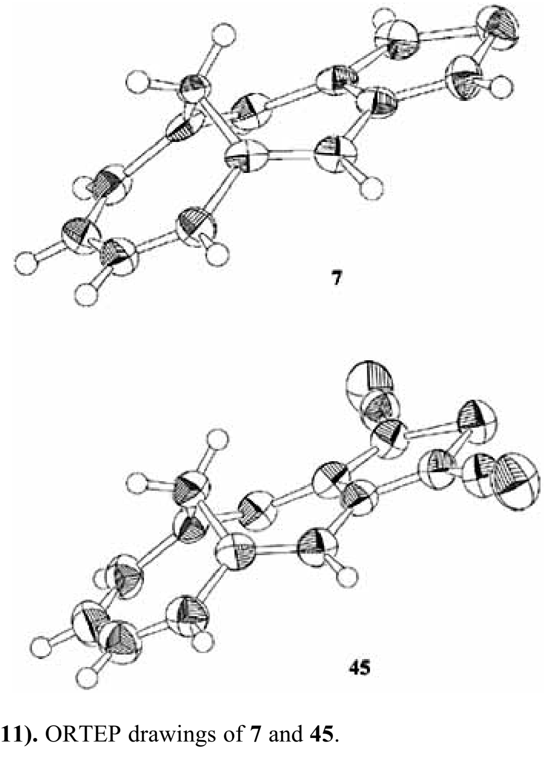


Fig. (11). ORTEP drawings of **7** and **45**.

NMR study of these compounds clearly indicates that the 1,6-methano[10]annulene part is atropic. The results are also supported by the explicit bond alternation observed in the X-ray structures (Figs. (**11**) and (**12**)). Therefore, in these molecules the thiophenes stay as aromatic and the methano[10]annulene parts are olefinic as seen in benzo-annulated 1,6-methano[10]annulenes in contrast to the case of **44**.

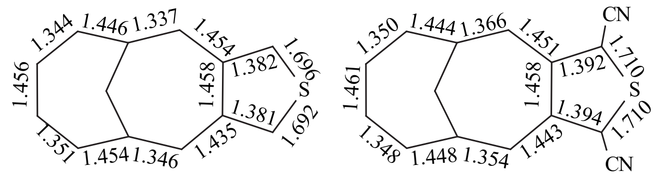


Fig. (12). The bond lengths (Å) of the crystal structures of **7** and **45**.

APPLICATION OF SUBSTITUTED 2,5-DIPHENYL 1,6-METHANO[10]ANNULENE FOR ORGANIC ELECTROLUMINESCENT DEVICES

The 2,5-diaryl-1,6-methano[10]annulenes show long-wave absorption maxima at a UV range of 350-380 nm with fairly moderate extinction coefficients and some of them were found to be luminescent. Application of these diaryl derivatives with suitable substituents at their phenyl rings to a light-emitting material in organic electroluminescent (EL) devices was reported by researchers at Toyota Central R&D Laboratories [33]. Two new derivatives, **4g** and **4h** (Chart **4**), for this purpose were prepared according to the method of Scheme **3**. The absorption maxima of **4g** and **4h** in neat thin film were observed at 370 and 396 nm and photoluminescence (PL) at 488 and 510 nm, respectively. The EL properties of fabricated devices using **4g** and **4h** as a light-emitting material shown in Fig. (**13**) are as follows. The devices showed the EL peaks at 479 nm (light-blue) for **4g** and 503 nm (green) for **4h**. The luminescent maxima of the devices were 2410 cd/m^2 at 220 mA/cm^2 for **4g** and 6420 cd/m^2 at 330 mA/cm^2 for 4h. The external quantum efficiencies at 400 cd/m^2 were found to be 0.8% (**4g**) and 1.4% (**4h**). These compounds have a structure of the slightly bending π-electron molecular plane with a projective methylene bridge unit as seen in the X-ray crystallographic structure of **4c**, though generally planar molecules are thought to be favorable for transporting hole and electron in thin layer devices. It is surprising that despite such structural features these compounds show promising organic EL properties. In other words, the results indicate that incorporation of the three-dimensional carbon framework into molecular structures of organic EL materials is possible. We hope that this concept in molecular design of EL materials can be extended to develop a practical material in electric device fields.

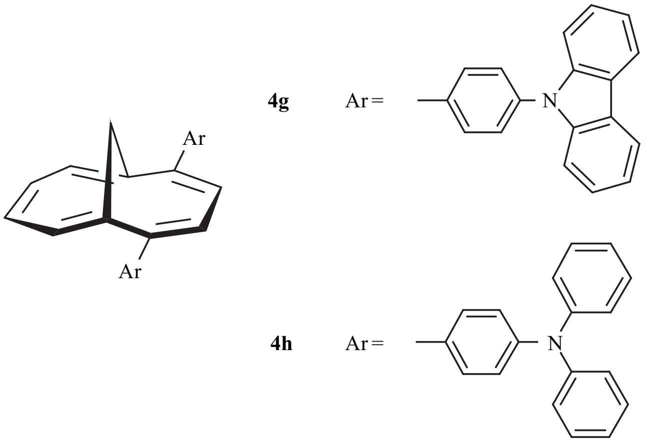


Chart 4. Substituted *bis*(aminophenyl)-1,6-methano-[10]annulenes for a light-emitting material.

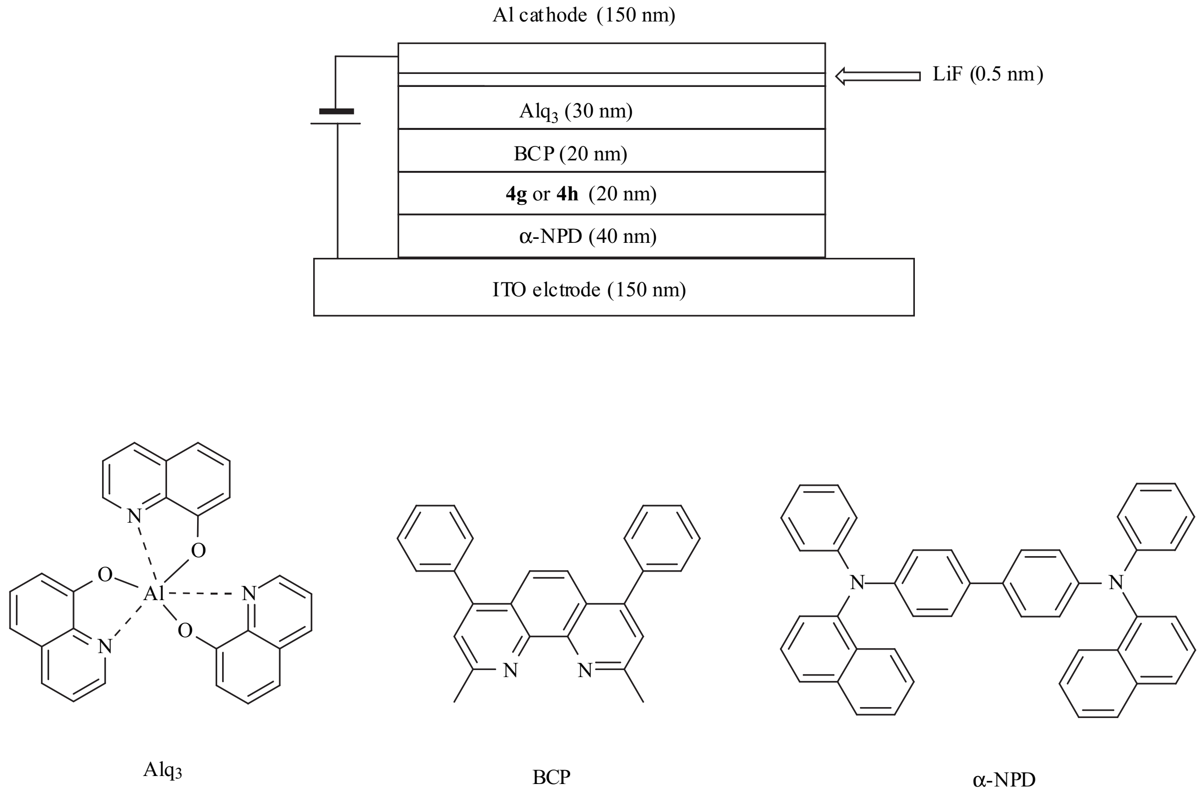


Fig. (13). The EL device structure and molecular structures of materials used.

SUMMARY

Preparation of 1,6-diacetyl- and 1,6-diformyl-1,3,5-cycloheptatrienes is relatively facile. An effective synthetic maneuver from these cycloheptatriene derivatives has been developed toward various 1,6-methano[10]annulenes, such as cylcobutene-annulated, thiophene-annulated and diaryl-substituted derivatives and its quinodimethane-type compound and 4,9-methanothia[11]annulenes. Accompanied with synthetic success, the results on the crystal structure analysis of the annulenes and discussion of mechanistic details of a key cyclization step yielded interesting structural features in annulene chemistry and also application of some annulene derivatives to a material in organic electroluminescent devices provided the novel conception in the molecular design. As an ending remark, we confidently claim that the field of annulene chemistry is still a fertile area even after the great achievements by Prof. E. Vogel.

ACKNOWLEDGEMENT

We dedicate this mini-review to Professor Dr. Emanuel Vogel. We thank Mr. Shuzo Tomoda, Shinji Furuta, Toyohiko Saito and Akihide Taketani and Ms Yuko Wada, Mizuho Nagai, and Chiharu Hayakawa at University of Toyama for their technical assistance for the unpublished synthetic works described here. We also thank Rigaku Inc. for X-ray crystal structure analysis of annulene **4c**. This study was supported partly by a Grant-in-Aid Scientific Research (No. 08640677 and 10640513 to S.K. and 09640631 and 13640528 to M.O.) from the Ministry of Education, Science, Technology, Sports and Culture, Japan.

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[13] Kuroda, S.; Fukuta, A.; Nguyen, C. T.; Oda, M. unpublished results. The X-ray data for **4c**: $C_{25}H_{22}$, Mw = 322.45, 0.40 x 0.10 x 0.05 mm^3, monoclinic, space group $P2_1/n$ (#14), a = 15.389(3), b = 4.647(2), c = 26.708(4) Å, β =105.78(2) deg, V = 1838.1(8) $Å^3$, Z = 4, D_{calc} = 1.165 g cm^{-3}, μ(Mo-$K\alpha$) = 4.92 cm^{-1}, 1212 independent reflections, 227 parameters, R = 0.037 (I > 2_(I), 724 reflections), wR = 0.052, S = 1.26, T = 296 °K. Estimated standard deviations for the bond lengths and angles are 0.004–0.006 (ang) and 0.3-0.5 (deg), respectively, for the non-hydrogen atoms. Crystallographic data excluding structures have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication numbers CCDC 607164. A copy of the data can be obtained free of charge from CCDC, 12 Union road, Cambridge CB2 1EZ. UK [DIRECT LINE: +44 1223 762910, Fax: +44 (0) 1223-336033 or e-mail: linstead@ccdc.cam.ac.uk; deposit@ccdc.cam.ac.uk.

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